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NASA Contractor Report 198455

Enhancing the Capabilities of NASA Lewis' 8×6/9×15 Wind Tunnel Complex Through Drive System Modifications

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February 1996

Prepared for
Lewis Research Center
Under Contract NAS3–27186

National Aeronautics and
Space Administration

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KEYWORDS

Subsonic Testing, Wind Tunnel Drive, Wound Rotor Induction Motor, Distributed Control Systems, Electrolyte Cooling

ABSTRACT

This paper describes the conclusions to date derived from a series of activities that began in January of 1995 to determine the potential power savings from running a three motor tunnel drive system on less than a full complement of three motors. This paper also discusses the now proven fact that one motor's minimum operating speed in this type of drive train is inherently slower than the minimum speed of three motors running at the same set of operating characteristics, as well as the benefits derived from this method of operation. The tunnel drive consists of three mechanically-coupled 29,000 HP wound rotor induction motors driving an axial flow compressor. Liquid rheostats are used to vary the impedance of the individual motor rotor circuits, thus varying the speed of the drive system. The resistance of the electrolyte in the rheostat tanks is inversely proportional to temperature. This paper discusses the manipulation of these factors to enhance the overall operation of the facility.

INTRODUCTION

The 8x6 Ft Supersonic Wind Tunnel (SWT) and 9x15 Ft Low Speed Wind Tunnel (LSWT) complex shown in Figure 1 offers a unique combination of wind tunnel conditions for both high speed and low speed testing. Prior to the work discussed in this paper the 8x6 SWT test section offered airflows ranging from Mach 0.36 to Mach 2.0 for both aerodynamic testing of inlets and nozzles or propulsion testing using burning jet and rocket engines. Capabilities for testing at subsonic and near-ground regimes is offered by the 9-ft high, 15-ft wide test area in the return leg of the facility. Air speed in the 9x15 LSWT test section can range from 0 to 175 mph (0.23 Mach), and in the past was varied using a combination of compressor speed and the position of the tunnel flow-control doors(shown as door #1 and #2 in Figure 1). In the past when very slow speeds were required in the 9x15, these doors might be very nearly full open, bleeding off large quantities of air--even with the drive system operating at its previous minimum speed of about 510 rpm. Power consumed during this mode of operation varied between 16 and 18 megawatts depending on test conditions, but clearly much of this power was not being used to provide air in the test section.

It can be easily argued that the air exiting the tunnel flow control doors represents wasted power and thus wasted money. It is the purpose of this paper to describe the changes made to the tunnel's drive system operation to eliminate much of this waste and enhance the overall operation of the facility.

DRIVE OPERATIONS BACKGROUND

The testing requirements for the two wind tunnels in a common loop make wide demands on the drive control system. Historically, the drive motors might be operated at speeds ranging between 510 and 875 rpm, depending on which tunnel was testing and the requirements of the test. The key to the tunnel's ability to vary speed over such a large range lies in the fact that the drive is driven by three wound rotor induction motors, each rated at 29,000 HP, which are equipped with brushes and slip rings on their rotors which allow for the insertion of varying external resistance into their respective rotor circuits. It is the varying of this rotor resistance that allows for such a wide range of speeds on such a large drive system.

The resistance is added to the rotor circuits using liquid rheostat tanks filled with an electrolyte liquid historically consisting of a 1% sodium carbonate solution. Movable electrodes are raised and lowered into the electrolyte solution via servomotors receiving commands from the tunnel's Distributed process Control System (DCS) to the individual motor's servo controllers (see Figure 2). The higher the movable electrodes are in the rheostat tank, the more resistance for a given temperature that exists in the rotor circuit, and thus the slower the drive or motor speed attainable.

The electrolyte solution's resistance varies inversely with temperature, thus the electrolyte is more resistive at low temperatures than at higher temperatures. The drive system shares one common electrolyte system for all three motors. The entire system is equipped with a heat exchanger utilizing externally supplied cooling tower water to maintain a desired electrolyte temperature. This electrolyte cooling system is also controlled by the tunnel's DCS.

Prior to the work described in the remainder of this paper, the electrolyte temperature setpoint was set at 55 degrees C regardless of whether the tunnel was running supersonic testing in the 8x6 or subsonic testing in the 9x15. This temperature allowed for good speed control during supersonic testing even though the movable electrodes may be very nearly at the bottom of the electrolyte tanks. We have come to learn that this temperature can play a key role in subsonic testing in either facility.

For subsonic testing (the primary focus of this paper), maintaining a selected compressor speed over a range of 510 to 875 rpm is essential because it directly affects the test section velocity. Therefore, any changes made with the goal of improving subsonic test conditions in either test section would have to be compatible with existing goals and capabilities. These requirements emphasize the need for a reliable, flexible, and accurate speed control system, as well as an equally robust electrolyte control system.

IDENTIFYING PROBLEMS AND OPPORTUNITIES

Subsonic testing at Lewis and around the country seems to be experiencing a resurgence in recent years. The ongoing changes in military requirements and the renewed focus on civilian transport problems, such as engine noise, are probably responsible for this renewed interest. NASA Lewis itself has limited subsonic testing capabilities as far as larger scale test facilities are concerned. Many of Lewis' existing subsonic test facilities have active test schedules spanning several years into the future.

All governmental testing facilities are under increased pressure to improve productivity and reduce operating costs. NASA Lewis is by no means immune from this intense and politically volatile economic environment.

The previously mentioned historical minimum drive operating speed of 510 rpm constrained the 8x6/9x15 facility's ability to test at some subsonic conditions. The aforementioned mode of operating the 9x15 subsonic test section clearly indicates that much of the power used to maintain the previous minimum drive speed of 510 rpm was being wasted via the air exiting the tunnel flow control doors ahead of the test section.

During the normal start sequence of the 8x6/9x15 drive system the individual drive motor starts are staggered by a series of software timers implemented through the DCS that works in concert with the drive speed control system. These timers are set to start the drive motors at 40 second intervals in order to meet power distribution system surge load requirements.

When the first drive motor comes on line its respective rotor current ramps up very rapidly to roughly 50% of full load rated current. This relatively low starting current is due to the external resistance inserted in the rotor circuit via the liquid rheostat tanks, which is maximized at motor start precisely for the purpose of minimizing inrush current to the motors. As the drive system begins to accelerate, the rotor current, having already peaked, begins to decay prior to the start of the second motor.

It is this rotor current decay coupled with the problems and inefficiencies listed above that spurred this author to investigate the feasibility and potential benefits that might be possible with a "One Motor Drive" run. The decaying rotor current prior to the start of the second motor indicated two things to this author: First, that one motor could safely run the drive by itself at some range of speeds given that the motors are individually rated for 2850 amps of rotor current and that the peak starting current was less than half this amount. Second, and more importantly, that the minimum speed attainable, while not immediately known or predictable, would have to be something less than the 510 rpm minimum that the drive was currently constrained to during three motor operation.

It then seemed an intuitive conclusion that one motor would use less electrical power than three motors while operating at speeds less than the previous 510 rpm and that lower drive speeds would naturally equate to some lower testing speeds than were previously attainable.

PROPOSED SOLUTION AND ASSOCIATED CONCERNS

Armed with the knowledge of the electrical operating characteristics of the facility, the historical electrical power inefficiencies of the current subsonic testing methods, and the need for NASA to improve its cost of operations at any possible level, this author proposed running the drive system on only one motor to see what range of speeds might safely be attainable and what power saving might be achieved via this method of operation.

Several problems needed to be addressed prior to attempting "One Motor Drive" operation. Some of these concerns were raised by the author but most were raised by others including operators, engineering peers and various levels of management. Each of the major concerns will be stated and addressed in the paragraphs that follow.

Concern - Rotor heat

One of the greatest enemies to a wound rotor induction motor is rotor heat. With the goal of reduced motor speeds comes increased slip. The slower a wound rotor induction motor is run the larger the slip becomes. Engineering peers and management alike were most concerned with the potential for rotor overheating in the motor as a result of operating the powered motor at a speed much slower than normal and also driving the entire load of the motor-compressor system with a single motor.

Addressing The Concern of Rotor heat

While the drive motors in this wind tunnel drive system are indeed wound rotor induction motors the presence of the slip rings and rotor brushes changes the scope of the picture just a bit. Indeed we are inserting additional resistance in the rotor circuit to minimize starting currents as well as vary the speed of the drive once the motor(s) is(are) running. The key point to note here though is that this resistance is not actually being inserted into the motor itself but rather externally via the liquid rheostat tanks. Therefore, while slip increases with decreased speed, as does the rotor circuit losses, any heat associated with these losses is primarily dissipated in the liquid rheostat tanks. It is also important to keep in mind that as the rotor resistance is increased the motor is slowing down, and as the motor slows down the rotor current is being reduced. Since current is the squared term in the I^2R heat loss equation the net result is less overall heat created in the rotor circuit. Lastly, since only one motor is running, only one motor is putting any heat that is created into a rheostat cooling system designed to handle the cooling needs of all three motors running at very high currents.

In an effort to back up these intuitive conclusions this author decided to implement an infrared (IR) camera system to view the air gap and the end of the rotor core through an inspection opening in the end of the motor housing. The IR camera was able to clearly show the air gap and the ends of the rotor slots as well as the connections for the stator windings all in the same small field of view. Historical data was gathered while the drive was running for prolonged periods of time on three motors. Data was gathered to compare the IR temperatures for motor #1 versus those for motor #3 at the opposite end of the drive train. The camera was then employed during the series of one motor test runs, and no significant change in recorded IR temperature data was noticed. In fact when the drive ran on one motor at near maximum one motor drive speeds approaching 600 rpm the recorded IR temperatures were the highest (about 122° F). However, when the drive then slowed down below 400 rpm the IR camera clearly showed the motor cooling down into the low 90° F range very quickly. The author believes this proves that running the drive on only one motor does not present a rotor heating problem.

Concern - Electrolyte Temperature Stability

The second major concern relates to electrolyte temperature stability. It has already been mentioned that during subsonic testing drive speed is directly related to the speed of the air in the test section and therefore stable drive speed is crucial for successful testing. It has also been mentioned that the electrolyte has a greater resistance when it is cold. Since one of the desires of running the drive on one motor is to see how slow the motors can be run, we naturally want to cool the electrolyte to the maximum extent possible. However, since the resistance in the tanks is higher than for normal running, more heat is being dissipated in these tanks. If this heat can not be transferred out of the electrolyte system quickly enough then an undesirable drift in drive speed due to temperature change might occur, which could impair testing capabilities.

Addressing The Concern of Electrolyte Temperature Stability

With one motor running at minimum speed the position of the rheostat tanks' moveable electrodes is very nearly at the top of the rheostat tanks which provides maximum resistance. Rotor current for the one motor, while flowing through this increased resistance, is creating heat that is being dissipated in an electrolyte system designed to cool three rotor circuits, not just one. As a result, the cooling capacity for removing the heat created from just the single motor running is significantly improved.

When the single drive motor is first started there is an immediate rise in electrolyte temperature while the slower electrolyte control loop attempts to track to the set point temperature. Experience derived from the one motor testing runs seems to indicate that the limits of the present cooling system will permit a set point temperature no lower than 35° C. This, of course, is very dependent on external climatic conditions since, as mentioned previously, the system uses a cooling tower to cool the heat exchanger. Without drastically modifying the cooling system itself it is clear that there are practical limits to what can be accomplished with the existing electrolyte cooling system. However, the system's ability to maintain a stable 35° C setpoint (after a short settling period) at very low speeds appears to be adequate.

It is important to note that the current system cannot maintain this very low temperature at all "One Motor Drive" speeds. As the single motor drives the compressor at higher speeds, the higher currents with only slightly improved slip do start to get the better of the electrolyte cooling system. Once the valve that feeds cooling tower water to the heat exchanger is in a full open position, there is nothing more the system or the operator can do to reduce the electrolyte temperature. However, since the drive is no longer attempting to operate at a pure minimum speed, it really does not matter if the electrolyte temperature drifts up a bit as long as it stabilizes with each speed set point. Fortunately it does just that. The reader is advised that more losses are being incurred as heat is dissipated in the electrolyte system; but that these are easily outweighed by the power savings from having only one motor running up to a certain crossover point that will be discussed later.

In general then, without significantly modifying the existing electrolyte temperature cooling system, there are limits to what can be accomplished with only one motor running. Within these boundaries though, the electrolyte temperature stability is not a problem for one-motor operation.

Concern - Additional Maintenance For Single Running Motor

Since the proposed new mode of operation had not been tried before, it may be possible that some additional maintenance concerns could surface relative to running the drive on a single motor. While this topic is still being investigated, it is appropriate to discuss some of issues that have been addressed to date.

Addressing The Concern Of Maintenance And Running On One Motor

Over the last seven years the 8x6/9x15 Wind Tunnel at Lewis has averaged between 300 and 400 hours of run time per year. It is hoped that the increased ability to do subsonic testing would enhance the marketability of the facility such that the number of run hours per year would be increased. However, even if the number of run hours was to double, the added duty cycle to machines of this nature seems (at least to this author) to be insignificant. All of the current maintenance programs tied to operating hours such as checking insulation integrity with a meggar, motor inspections and lubrication system maintenance, are being re-examined to take into account this potential added duty cycle.

Since, as has been discussed, there is no heat problem associated with running the drive on a single motor; it is not anticipated that issues such as insulation degradation should need to be specifically addressed, as long as operating conditions for the single motor stay within the nameplate data, which is the case.

One area of concern has surfaced regarding the motors not running during "One Motor Operation". The concern is a brush wear issue for the non-running motors #2 and #3. It seems that the brushes in the free wheeling motors do not develop proper lubricating conditions without the presence of current in their respective rotor circuits. Some damaged brushes were found during the first motor inspection that occurred after 100 hours of running mostly single drive motor runs. Also, a dark glaze was found to be forming on the slip rings for motor #3 indicating a potential problem down the road. The appropriate NASA Lewis personnel have been in contact with the brush supplier who has recommendations for supplying brushes to meet these new needs and still provide reasonable brush life. After reviewing these recommendations, new brushes will be tested and then changes implemented, as required, based on the results.

Detailed motor inspections will continue to be performed with close attention paid to additional problems that may surface as a result of running the drive for prolonged periods on a single motor. It is not anticipated at this time that any condition would arise that would prohibit or otherwise render it impractical to pursue this cost saving, facility enhancing mode of operation.

SUMMARY OF RESULTS

The first "One Motor Drive" run was performed on January 9, 1995. This test was limited by management to only five minutes and was accomplished by simply delaying the start of the second motor by adjusting the appropriate software timer from 40 seconds to 5 minutes. Figure 3 shows a 10 minute trend, plotted using the DCS's trending function. Four key system parameters: Drive Motor RPM, Motor #1 Rotor Current, Total Power and Electrolyte Temperature were plotted.

This plot clearly shows that the motor current peaks and begins to decay in less than one minute's elapsed time. The rate of decay is much slower than historical plots where the second motor would have come on line after 40 seconds to aid in the acceleration of the drive. Nevertheless, it is this decay in rotor current that prompted the author to attempt this mode of operation in the first place. The 5 minute test proved to be just a little short yet it can be seen in the figure that the drive is approaching some steady state speed apparently in the low 300 rpm range.

As all other indicators looked promising from the first test, a second 15 minute test was performed on January 17, 1995 in order to find the true steady state minimum speed. By now the software had been modified to accept one motor operation. After about 6 minutes time the drive had settled out at a speed of only 337 rpm, **more than 160 rpm slower than the drive had ever been run before.** This drive motor speed translates into an 8X6 test section speed of 0.25 Mach. The DCS plot for this run looked identical to the five minute run with the rotor current settling in at just over 700 amps against a rating of 2850 Full Load Amps. Electrolyte temperature also stabilized at just over 29° C, but it should be noted that since this test was conducted in January it was extremely cold outside and thus the cooling tower efficiency was greatly increased.

Armed with the results of these two tests, an intense research study was conducted to verify that this mode of operation was acceptable for large induction machines. The Large Motors Divisions of General Electric and Westinghouse were consulted as well as various members of academia familiar to the author. These external contacts coupled with many hours of reading technical journals and textbooks eventually led the author to conclude that machines of this type can be run at speeds potentially as low as 25% of their synchronous speed, the practical limit being the ability to vary the resistance of the rheostat tanks to a sufficient extent to achieve control over the desired speed range.

In order to chart the new capabilities of "One Motor Drive" operation, a full load test was conducted on March 17, 1995. During this test the drive speed was varied in 25 and 50 rpm increments to determine how high of a speed could safely be achieved with one motor operating the drive. It was decided that the motor would not be loaded beyond 90% of rated rotor current load. The results of this test showed that under normal tunnel conditions one motor could run the drive up to about 600 rpm but required almost 19 megawatts of power to accomplish this. These results are shown on a plot in Figure 4. Figure 4 also shows a subsonic Power versus Drive RPM plot for three motor operation with cooled electrolyte and also the results of a two motor test conducted in August in order to examine all possible drive operation scenarios. It can be clearly seen from the plot that there is little to be gained from pushing one motor beyond 560 rpm and no practical gain from running the drive on two motors under normal test conditions. The one motor drive portion of the curve is not smooth because we did not wait for the electrolyte temperature to become perfectly stable at every data point. We were primarily interested in plotting the general trend of power versus load for the tunnel.

An upper limit of 560 rpm or 15 megawatts has thus been set for prolonged one motor operation. Spot data points can be pursued via one motor operation at drive speeds up to 600 rpm and power loads up to 19 megawatts for test periods not to exceed 1 hour. If prolonged testing at these speeds is required, then motors #2 and #3 are to be brought on line. The drive software has been further modified to allow this to be done without shutting the drive down, as was previously necessary. This enhancement further expands the functional testing capabilities and overall productivity of the facility.

WHY DOES IT WORK

With some of the results already discussed the reader may be curious at this point as to why the drive system would run so much slower on one motor than on three and why, in over 45 years, no one had ever tried this mode of operation before. The answer to the first part of this question is remarkably simple and will be discussed next.

It was mentioned in the above section that it was the decaying rotor current on motor #1 during a normal start sequence that clued this author that it may indeed be possible to run the drive on only one motor. Since the motor current does indeed decay the load curve for one-motor operation shown in Figure 4 was somewhat expected. If one combines the results of the one motor and three motor data shown in Figure 4 and smooths the results a bit, a somewhat continuous load curve can be created for the new total drive operating range. This new "Load Curve" has been approximated in Figure 5.

The next key to the puzzle comes from the drive's individual and combined motor "Torque versus Speed" curves, which have been approximated and superimposed on Figure 5 as well. An induction motor with a fixed rotor resistance (i.e., a squirrel cage rotor) has a value of starting torque at zero speed that is less than the maximum torque available from the motor. As one inserts greater and greater resistance into the motor's rotor circuit, the typical torque/speed curve becomes flatter and flatter until, as shown in Figure 5, maximum torque is made available on motor start up. The actual characteristic curves for these drive motors are proprietary to the manufacturer and were unavailable to this author. However, for purposes of explaining the theory behind one motor versus three motor operation the approximations made in Figure 5 will suffice.

With only one motor operating at steady state conditions with its individual rheostat sticks in their maximum resistance position, the lower torque speed curve in the figure has been approximated from the experimental data. Since only one motor is supplying torque to the drive train, the intersection of the torque/speed curve with the smoothed load curve gives a single speed data point that is the steady state operating speed under these conditions (refer to speed point S_{M1} in Figure 5). When the second and third motor are brought on line (at speeds below 240 rpm and thus not shown in the figure) three times the torque is available to accelerate and operate the drive for any given speed. This creates the upper torque/speed curve shown in Figure 5. The rheostat sticks for all three motors are still in their respective maximum resistance positions when the torque/speed curve intersects the load curve. The upper torque/speed curve thus creates the steady state speed point S_{M3}. Thus, one motor inherently runs slower than three motors under the same per motor operating criteria.

As to why this method of operation was never attempted in the past this author can only speculate. Electrical power was relatively inexpensive back when this facility was designed and built. The facility was originally designed for supersonic operation with transonic capability added, in the late 1950's, when bleed holes were added to the test section walls. Subsonic operation was added in the mid 1960's with the 9x15 Low Speed Wind Tunnel built into the return leg. Many engineers are not well versed in large motor operation and assumed that one motor or three motors would run the drive at the same minimum speed, and that it would just take longer for the single motor to accelerate the drive to the steady state speed. All of these factors probably contributed to this productive and cost saving method of operation lying dormant for so many years.

CONCLUSION

Large multiple motor drive systems of the type described in this paper may be able to be operated over a wider range of speeds than originally thought. Significant electrical power savings can be achieved, if lower speeds are desired, by investigating running the drive system on only the number of motors required to achieve the desired test conditions.

Recently, during six weeks of testing at NASA Lewis Research Center, with a model in both the 8x6 and 9x15 test sections, an electric power cost savings of over $71,000 was achieved. This represents a savings of over 50% from what would have been required using historical modes of operating the drive system. Additionally, the 8X6 model was successfully tested at test section speeds down to 0.25 Mach, considerably slower than the 0.36 Mach subsonic minimum speed previously available.

There are additional methods to consider for further increasing the resistance of the rotor circuit and thus slowing the drive further. These methods include enhancing the electrolyte cooling system or reducing the electrolyte concentration below 1%. There are, of course, practical limits and any proposal's cost must be weighed against the potential for additional power savings and maintenance concerns created for the drive.

There is still a lot to be learned in the area of subsonic testing. In the future, cost and return on investment will play key roles in which areas can be explored. It is the job of operations engineers to continue to explore innovative ways of operating the facilities built long ago.

ACKNOWLEDGMENTS

This author would like to acknowledge the invaluable contributions of Marty Krupar for providing the mechanical engineering expertise to investigate the effects this proposed method of operation would have on the drive compressor and mechanical components; and Tim Bencic for his intimate knowledge of the 8X6's DCS and drive controls and his cooperative spirit in working to modify the drive control systems to accept one motor operation.

I wish to especially thank retired Professor Eugene Klingshirn formerly of Cleveland State University for providing his valuable knowledge, advice, and insight into the operating characteristics of wound rotor induction machines.

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8-BY 6-FOOT AND 9-BY 15-FOOT WIND TUNNELS

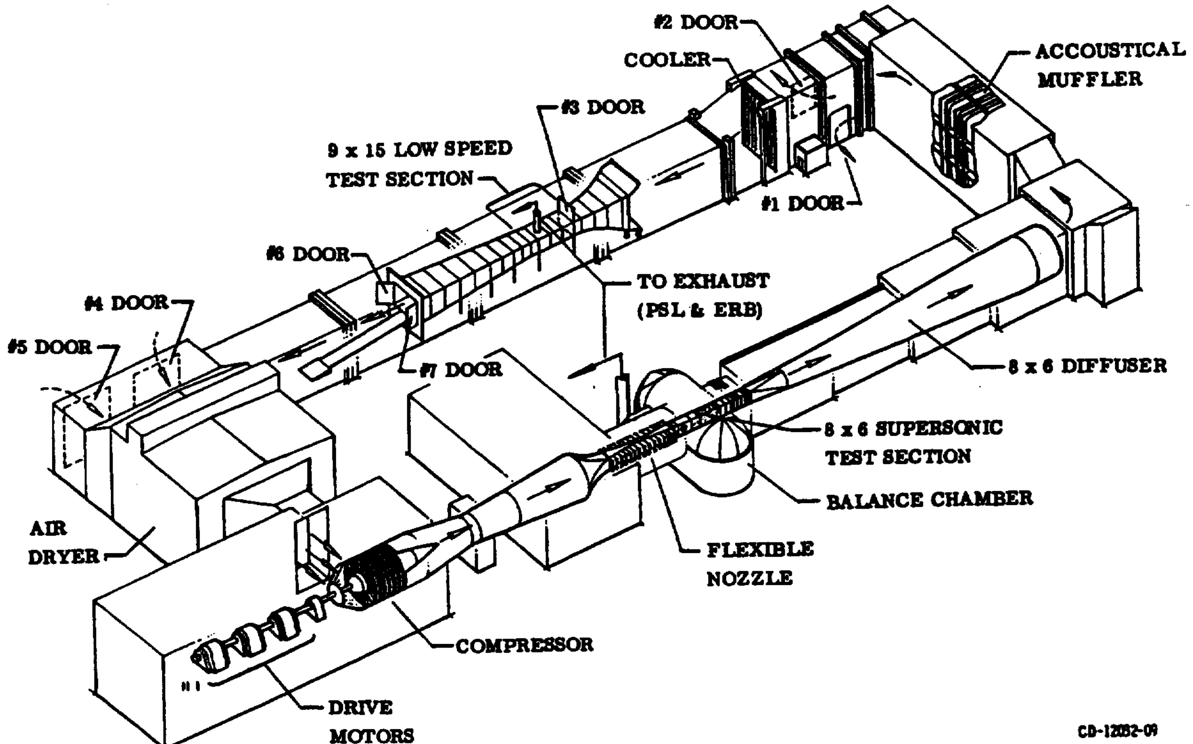


FIGURE 1

Drive Motor Speed Control Schematic

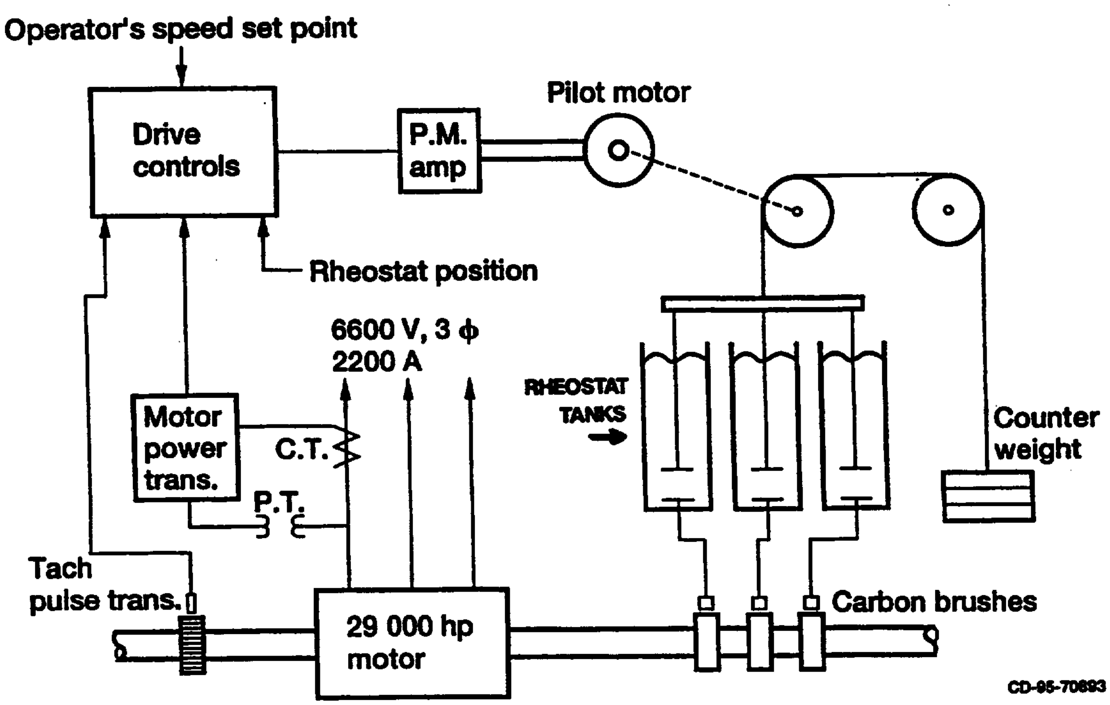
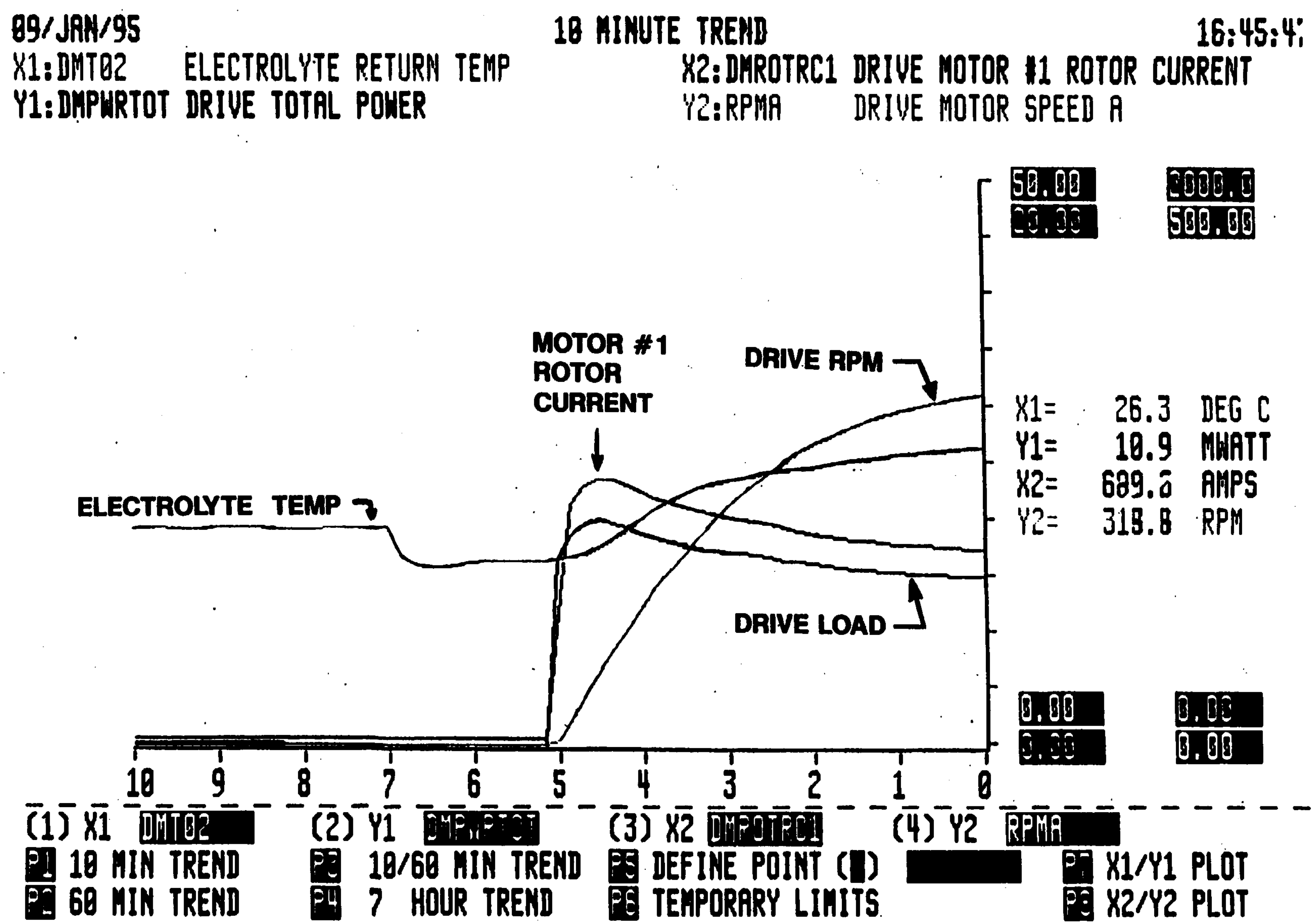


FIGURE 2



09/JAN/95
10 MINUTE TREND
X1:DMT02 ELECTROLYTE RETURN TEMP
Y1:DMPWRTOT DRIVE TOTAL POWER
X2:DMROTRC1 DRIVE MOTOR #1 ROTOR CURRENT
Y2:RPMA DRIVE MOTOR SPEED A
50.00
500.00
MOTOR #1 ROTOR CURRENT
DRIVE RPM
ELECTROLYTE TEMP
DRIVE LOAD
X1= 26.3 DEG C
Y1= 10.9 MWATT
X2= AMPS
Y2= RPM
10 9 8 7 6 5 4 3 2 1 0
(1) X1 DMT02
(2) Y1
(3) X2
(4) Y2 RPMA
10 MIN TREND
60 MIN TREND
10/60 MIN TREND
7 HOUR TREND
DEFINE POINT
TEMPORARY LIMITS
X1/Y1 PLOT
X2/Y2 PLOT

FIGURE 3

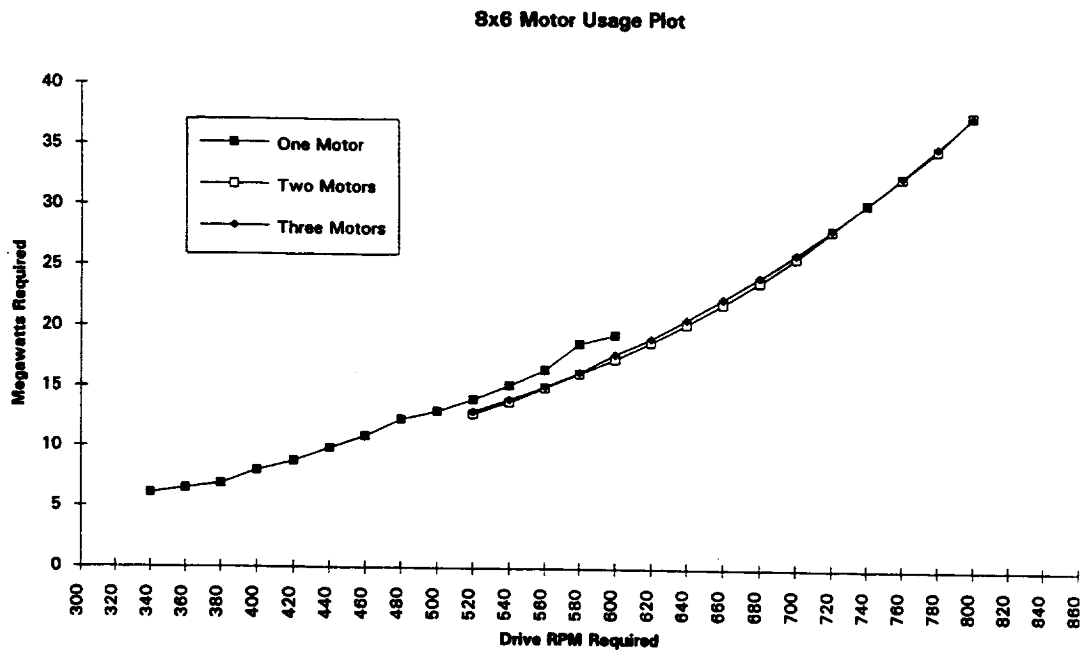


FIGURE 4

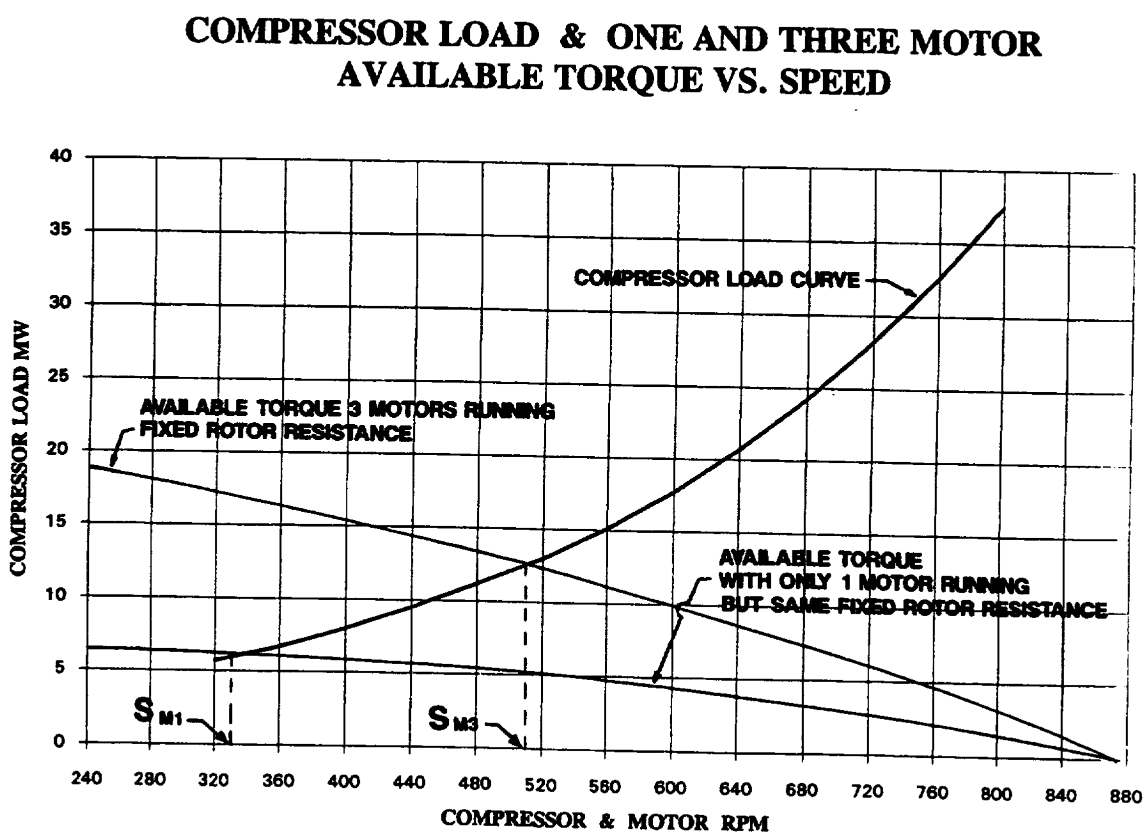


FIGURE 5

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
February 1996

3. REPORT TYPE AND DATES COVERED
Final Contractor Report

4. TITLE AND SUBTITLE
Enhancing the Capabilities of NASA Lewis' 8×6/9×15 Wind Tunnel Complex Through Drive System Modifications

5. FUNDING NUMBERS
WU–505–62–82
C–NAS3–27186

6. AUTHOR(S)
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7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
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8. PERFORMING ORGANIZATION REPORT NUMBER
E–10121

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135–3191

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
NASA CR–198455

11. SUPPLEMENTARY NOTES
Prepared for the 42nd International Instrumentation Symposium cosponsored by the Aerospace Industries and Test Measurement Divisions of the Instrument Society of America, San Diego, California, May 5–9, 1996. Project Manager, Sandra L. Hardy, Engineering Support Division, NASA Lewis Research Center, organization code 2850, (216) 433–2278.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Unclassified - Unlimited
Subject Category 09

This publication is available from the NASA Center for Aerospace Information, (301) 621–0390.

12b. DISTRIBUTION CODE

13. ABSTRACT ***(Maximum 200 words)***

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14. SUBJECT TERMS
Subsonic testing; Wind tunnel drive; Wound rotor induction motor; Distributed control systems; Electrolyte cooling

15. NUMBER OF PAGES
16

16. PRICE CODE
A03

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	

National Aeronautics and
Space Administration
Lewis Research Center
21000 Brookpark Rd.
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